# Sea Spray and Icing in the Emerging Open Water of the Arctic Ocean

Kathleen F. Jones
Cold Regions Research and Engineering Laboratory, 72 Lyme Road, Hanover, NH 03755
phone: (603) 646-4417 fax: (603) 646-4644 email: kathleen.f.jones@usace.army.mil

Award Number: N0001412MP20085

and

Edgar L Andreas
NorthWest Research Associates, Inc.; 25 Eagle Ridge; Lebanon, NH 03766
phone: (603) 448-3555 fax: (603) 448-3555 email: eandreas@nwra.com

Award Number: N00014-12-C-0290
http://www.nwra.com/resumes/andreas/

## LONG-TERM GOALS

The goal of this project is to develop the capability to quantify both the concentration of sea spray over the open ocean and the severity of sea spray icing on fixed offshore structures. We will use existing information on the relationship of the spray concentration distribution to wind speed (Lewis and Schwarz 2004; Andreas et al. 2010; Jones and Andreas 2012) to estimate the sea spray climatology in ice-free northern oceans from reanalysis data and the time-varying extent of the sea ice cover. Our field campaigns in the second and third years will focus on measuring sea spray parameters and relevant meteorological conditions to characterize spray drop distributions at high wind speeds and cold temperatures. Sea spray data at high wind speeds are sparse, and there are no measurements of the spray drop concentration at air temperatures below freezing. This effort directly addresses two of the focus areas in the core ONR Arctic program:

- Improving understanding of the physical environment and processes in the Arctic Ocean;
- Developing integrated ocean-ice-wave-atmosphere Earth system models for improved prediction on time scales of days to months.

## OBJECTIVES

Our objectives are as follows:

- Use reanalysis data to estimate spatially and temporally distributed sea spray concentrations over the northern oceans. This estimate is currently limited by the sparse information on sea spray at high wind speeds. Adapt the Andreas et al. (2008, 2010) spray algorithms for high wind speeds and subfreezing temperatures.
- Use these estimates of sea spray concentrations to characterize the icing risk for offshore structures in northern regions by adapting the heat balance calculation for freezing rain in Jones (1996) to saline drops and by modifying the Finstad et al. (1988) collision efficiency algorithm to take into account the larger mass of saline drops compared to freshwater drops.

# Report Documentation Page

*Form Approved*
*OMB No. 0704-0188*



| | | |
|---|---|---|
| 1. REPORT DATE<br>**30 SEP 2013** | 2. REPORT TYPE | 3. DATES COVERED<br>**00-00-2013 to 00-00-2013** |

| | |
|---|---|
| 4. TITLE AND SUBTITLE<br>**Sea Spray and Icing in the Emerging Open Water of the Arctic Ocean** | 5a. CONTRACT NUMBER |
| | 5b. GRANT NUMBER |
| | 5c. PROGRAM ELEMENT NUMBER |
| 6. AUTHOR(S) | 5d. PROJECT NUMBER |
| | 5e. TASK NUMBER |
| | 5f. WORK UNIT NUMBER |
| 7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)<br>**U.S. Army Corps of Engineers,Cold Regions Research and Engineering Laboratory (CRREL),72 Lyme Road,Hanover,NH,03755** | 8. PERFORMING ORGANIZATION REPORT NUMBER |
| 9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) | 10. SPONSOR/MONITOR'S ACRONYM(S) |
| | 11. SPONSOR/MONITOR'S REPORT NUMBER(S) |

12. DISTRIBUTION/AVAILABILITY STATEMENT
**Approved for public release; distribution unlimited**

13. SUPPLEMENTARY NOTES

14. ABSTRACT

15. SUBJECT TERMS

| 16. SECURITY CLASSIFICATION OF: | | | 17. LIMITATION OF ABSTRACT | 18. NUMBER OF PAGES | 19a. NAME OF RESPONSIBLE PERSON |
|---|---|---|---|---|---|
| a. REPORT<br>**unclassified** | b. ABSTRACT<br>**unclassified** | c. THIS PAGE<br>**unclassified** | **Same as Report (SAR)** | **9** | |

**Standard Form 298 (Rev. 8-98)**
Prescribed by ANSI Std Z39-18

- Determine the properties of sea spray in high wind speeds by making drop concentration measurements on fixed offshore structures or at well exposed coastal or island sites at air temperatures below freezing.
- Measure the density of ice accreted from sea spray on fixed structures and develop a relationship between spray ice density and weather parameters.
- Use our sea spray measurements to revise the Jones and Andreas (2012) spray concentration distribution for high wind speeds; update our initial icing risk analysis.
- Rapidly disseminate all data and metadata.

## APPROACH

Our goal is to quantify sea spray concentrations from wind-generated sea spray and the resulting spray icing on offshore structures, such as wind turbines and exploration, drilling, and production platforms. Our approach combines 1) the simulation of sea spray and icing from reanalysis data and data from moored buoys and coastal stations, 2) a field campaign to measure the liquid water content and median volume drop radius of sea spray in high winds, 3) the development of a spray concentration density function for high wind speeds, 4) the estimation of the spatial distribution of sea spray in all seasons, and 5) the determination of icing risk when the air temperature is below freezing in northern oceans.

To characterize the meteorological conditions in which we observe the spray in our field program on Mt. Desert Rock in the winter of 2012–2013, we are using the measurements archived by the National Data Buoy Center at C-MAN station MDRM1 and buoy 46034. These instruments provided mean wind speed and direction, temperature, and pressure, and wave height. Wind data are provided hourly as well as 10-min averages throughout each hour. Data from MDRM1 are not archived reliably by NDBC because of transmission problems. During gaps in the MDRM1 data, we use data from MISM1, on a nearby island. The locations of these stations and buoy are shown in Figure 1.

For the field program, we also deployed a full suite of turbulence instruments just above the high tide line (Figure 2) to determine the turbulent air-sea surface fluxes of momentum and sensible heat through eddy-covariance measurements.

We are planning a second month-long field campaign for the winter of 2012–2013 at Mt. Desert Rock.

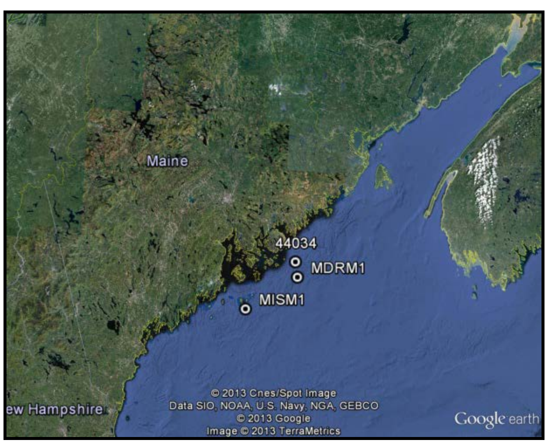


***Figure 1. Locations of C-MAN stations MDRM1 (Mt. Desert Rock) and MISM1 (Matinicus Rock) and NERACOOS buoy 44034 in the Gulf of Maine.***

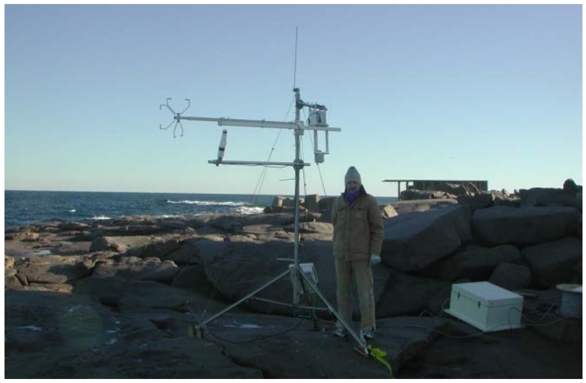

***Figure 2. Mast on which we measured mean meteorological quantities and the turbulent fluxes of momentum and sensible heat.***

The key CRREL personnel for this project are Kathy Jones, Chris Williams, and Kerry Claffey. We are working with Ed Andreas at NWRA. We borrowed Chris Fairall's Cloud Imaging Probe (CIP) for the field campaign in the winter of 2011–2012 . The data for the spray climatologies come from the National Data Buoy Center (NDBC) , the National Snow and Ice Data Center, and the National Centers for Environmental Prediction (NCEP).

## WORK COMPLETED

Our Winter Rock Experiment (WREx) was from 29 December 2012 to 28 January 2013. We collected sea spray drops on microscope slides from the lower catwalk on the lighthouse on Mt. Desert Rock to characterize the drop concentration distribution at 20 m above sea level (asl) for temperatures ranging from –15° to 9$^{o}$C , wind speeds up to 21.5 m/s, and significant wave heights up to 4.5 m. We used half-width microscope slides to get a higher collision efficiency of spray drops than is possible with standard slides. To provide a hydrophobic surface, the slides were covered with a thin layer of Vaseline. The exposure time of the slides is limited by the drop density on the slide; if the drops are too close together, they tend to coalesce. Immediately following a slide exposure, we photographed it using a microscope set up at the second level in the lighthouse. The temperature and humidity in this space were similar to the outside conditions. We typically captured 20 images from each slide.We also collected sea spray data using both the Cloud Imaging Probe (Figure 3) and microscope slides on the foghorn platform, which is about 7 m asl. The  spray drops there are dominated by local generation in the surf zone. We typically rotated the CIP once a day to align it with the wind direction.

We processed the slide images using Image Pro software to count and size the drops from the most interesting nine of the observations from lighthouse and from one observation on the foghorn platform when the CIP was aligned with the wind. The drop concentration distributions at the level of the lower catwalk on the lighthouse are shown in Figure 4a. Note that the highest drop concentrations are associated with the highest significant wave heights rather than the highest wind speeds. The highest wind speeds we sampled were from the northwest, with a fetch of only 32 km. Slightly lower winds from the southwest blowing parallel to the coast of Maine generated significantly higher waves. None of our samples are for $U_{10}$ > 20 m/s, which is the threshold for significant contributions of spindrift to the sea spray. These large spindrift drops dramatically increase the liquid water content of the spray. Our measured liquid water contents are shown in Figure 4b along with liquid water content profiles

***Figure 3. Cloud imaging probe and its associated sonic anemometer/thermometer mounted on the foghorn platform on Mt. Desert Rock.***

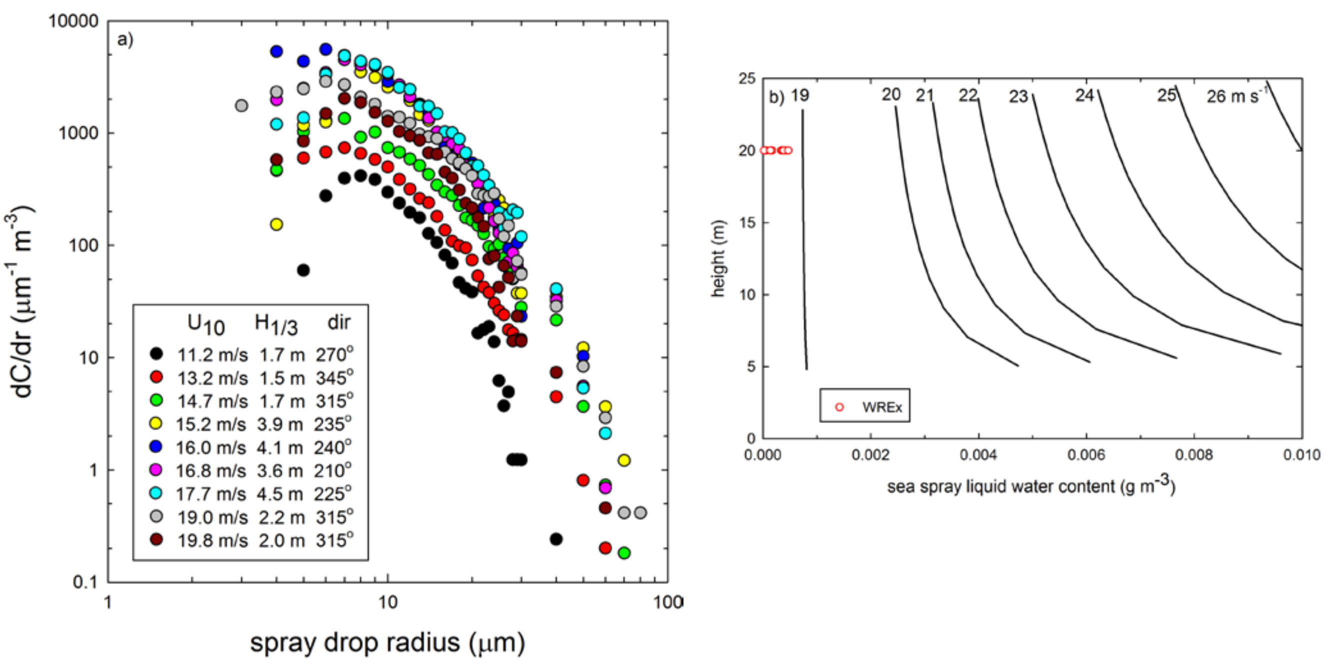


***Figure 4. Drop slide results: a) drop concentration distributions observed at 20 m asl on the lighhouse for wind speeds from 11.2 to 19.8 m/s, and b) spray liquid water contents from the concentration distributions in (a) compared to the expected liquid water content profiles for $U_{10}$ from 19 to 26 m s$^{-1}$.***

based on the Lewis and Schwarz (2004) canonical drop concentration distribution for $U_{10} < 20$ m/s, the Jones and Andreas (2012) extension to higher wind speeds, and the Fairall et al. (2009) equation to calculate the spray drop concentration aloft.

In a separate effort, we are analyzing NDBC data from buoys and coastal stations and North American Regional Reanalsysis (NARR) data from NCEP to develop a sea spray climatology. The reanalysis data is on a 35 km grid and has a 3-hour time step. Figure 5 compares measurements from MDRM1 in the winter of 2011–2012 with NARR data from the closest grid point, which is 14 km east of MDRM1. Relative humidities are calculated from the measured air temperatures and dew point temperatures using Lawrence (2005)

$$RH = 100 - 5(T_a - T_d).$$

In general, the reanalysis and measured data agree well. An example of generally poor agreement is provided in Figure 6 by NDBC buoy 46080 in the Gulf of Alaska and the nearest NARR grid point, which is 9 km due north. In this case, the measured and reanalysis wind speeds are similar, but there are significant differences between the measured and reanalysis air temperatures, relative humidities, and air pressures. Thus, while reanalysis data provides much better spatial coverage than measurements, they may not represent conditions at a particular location very well.

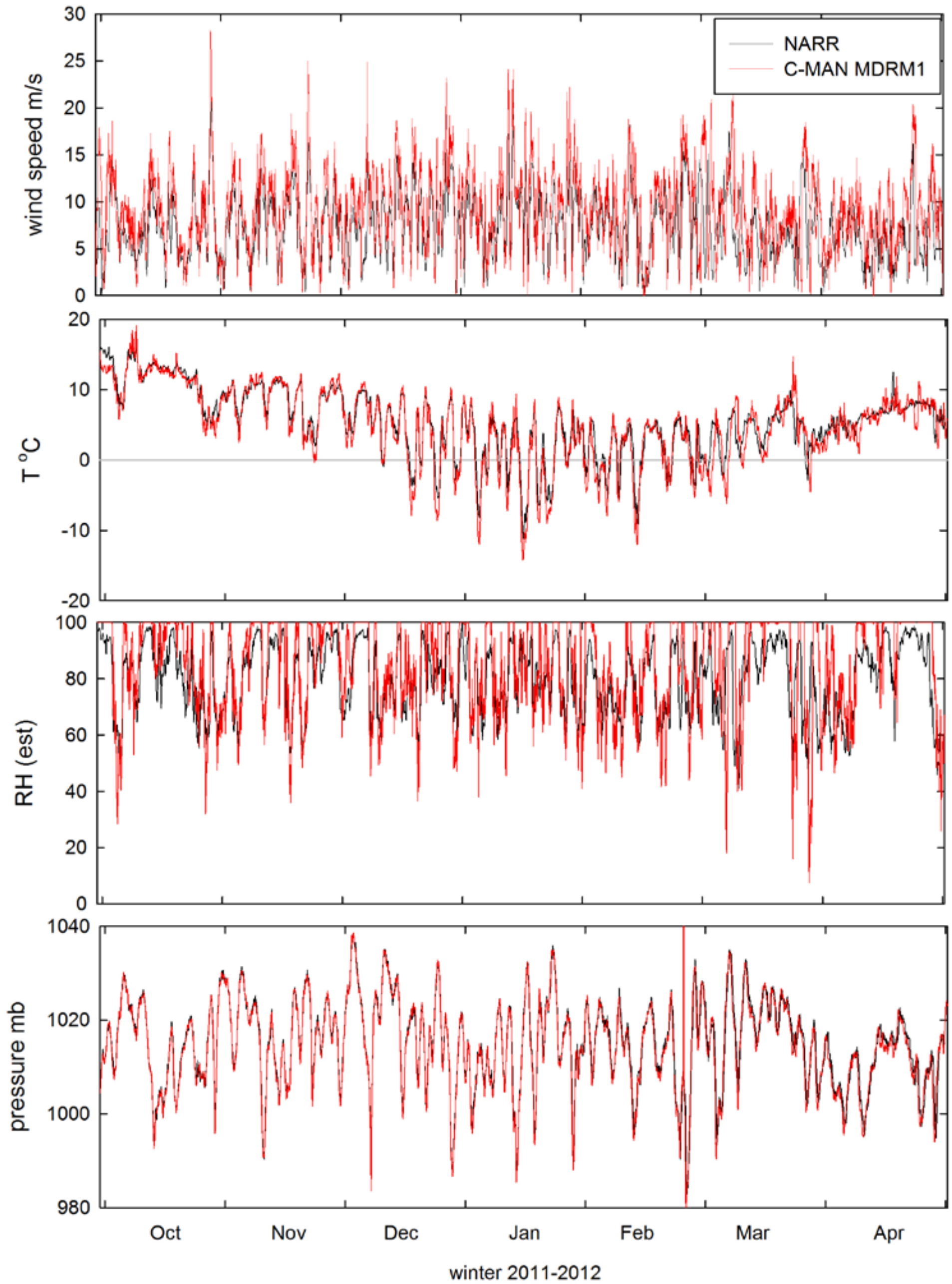


***Figure 5. Wind speed, air temperature, relative humidity, and pressure measured at MDRM1 and from the nearest NARR grid point for the winter of 2011ï 2012.***

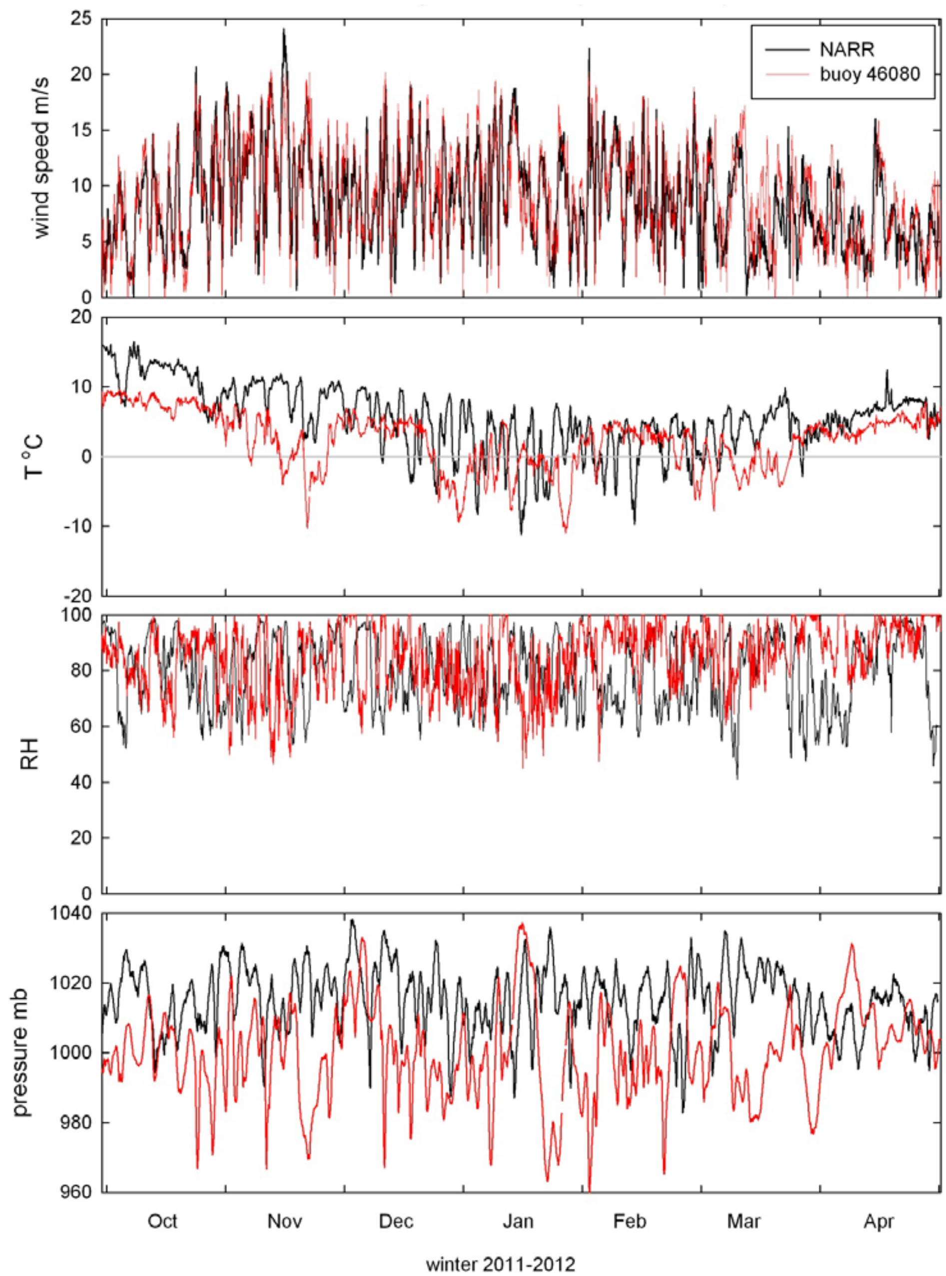


***Figure 6. Wind speed, air temperature, relative humidity, and pressure measured at buoy 46080 in the Gulf of Alaska and from the nearest NARR grid point for the winter of 2011ï 2012.***

We analyzed NARR data for the winter of 2011–2012 to determine the frequency of weather conditions conducive to sea spray icing on fixed offshore structures, assuming no sea ice. At each grid point, we counted the number of time steps from 1 October to 30 April with the air temperature at 2 m $0^{o}$C or colder and the wind speed at 10 m 20 m/s or higher. The results are mapped in Figure 7. The most frequent spray icing is in the Labrador Sea along the southern coast of Greenland. Other locations with many hours of spray icing are the Greenland Sea between Iceland and Greenland, the western

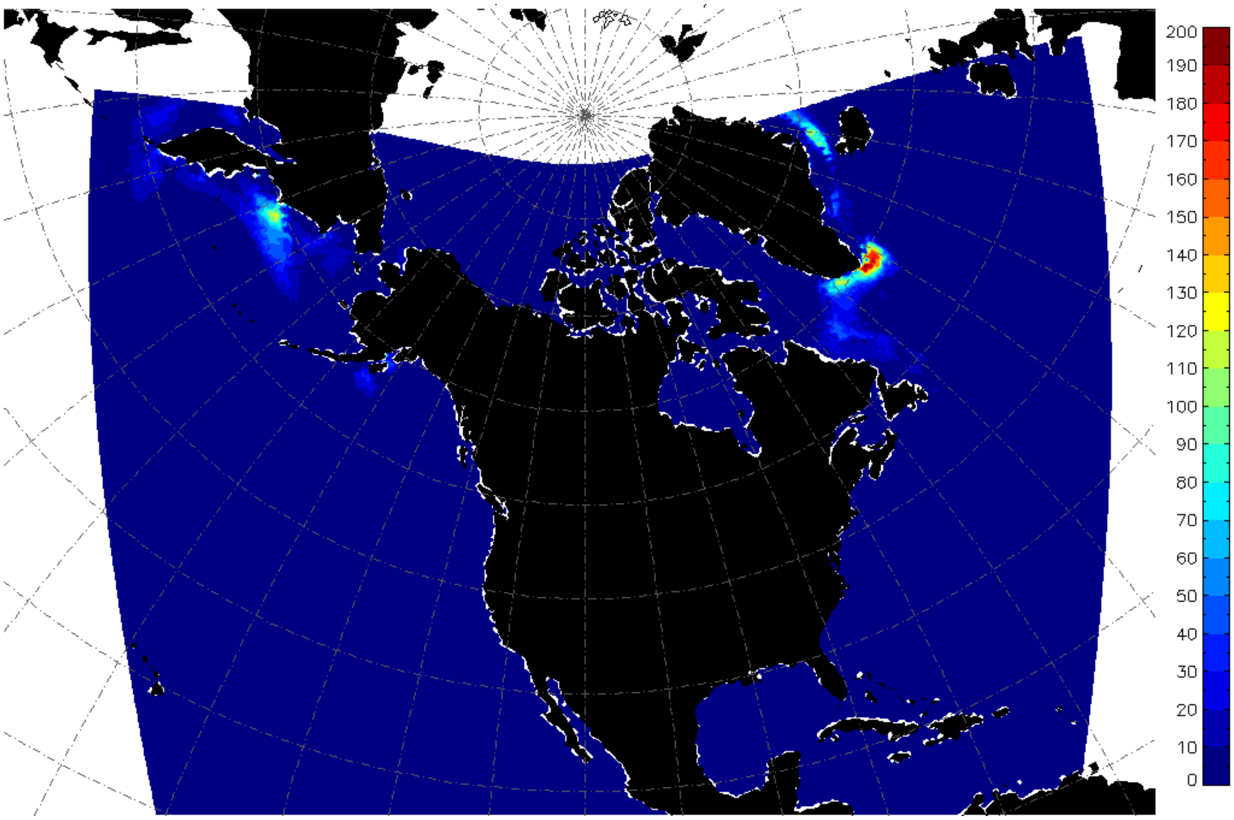


***Figure 7. Number of hours in the winter of 2011ï 2012 with weather conditions, assuming no sea ice, conducive to sea spray icing on fixed offshore structures; based on NARR data.***

Bering Sea near Siberia, and off the coast of southwest Alaska, including Cook Inlet, where the semi-submersible *Ocean Bounty* experienced a number of spray icing storms in the winter of 1979–1980 (Nauman 1984; Jones and Andreas 2012).

## RESULTS

We are focusing our field experiment on Mt. Desert Rock for the third year of this project, WREx 2, on answering questions raised last winter during WREx. We will measure the salinity of both individual sea spray drops and collections of spray drops to determine the drop size at formation and the freezing temperature of the sea spray. We will collect spray drops using full-width microscope slides to decrease the collision efficiency of the spray drops; this approach will allow longer exposure times and, thus, larger sample volumes. We hope to be there for wind speeds greater than 20 m/s. In those conditions, we will characterize the sea spray concentration distribution using multicylinder observations. Jones and Andreas (2013) estimate the required exposure times for multicylinders at 20 m asl for wind speeds from 20 to 30 m/s, assuming significant wave heights for unlimited fetch. These multicylinder observations would collect spray drops from sample volumes of about 1000 $m^3$ compared to less than 1 $m^3$ for the microscope slides.

## IMPACT/APPLICATIONS

- We are developing a sea spray climatology over the northern oceans. Sea spray impacts both fixed offshore structures and ships. We expect the sea spray climatology in the Arctic Ocean to change with the declining sea ice cover.
- The evaporation of the drops in the marine boundary layer affects the heat and mass transfer across the air-sea interface, which in turn influences climatology. Global climate models are sensitive to changes in the surface heat flux that are as small as 1 $W/m^2$. Spray-mediated heat fluxes are estimated to be much larger than this (Andreas et al. 2008).
- We are assessing icing risk for fixed offshore structures. When freezing spray that is generated by the interaction of wind and waves accumulates on such structures, it is a hazard for both personnel and the structure itself.

## TRANSITIONS

Journal articles and conference presentations document our work on sea spray and air-sea exchange.

Andreas has also developed a software "kit" that contains instructions and the Fortran programs necessary to implement a bulk air-sea flux algorithm. A bulk flux algorithm provides two-way coupling between the atmosphere and ocean in numerical models. In our research, though, it acts as the front-end for our spray concentration calculations by providing the turbulent surface fluxes and the near-surface vertical profiles of wind speed, temperature, and humidity. Version 3.4 of this algorithm is the one last described in the literature (e.g., Andreas et al. 2008; Andreas 2010). Andreas has, however, just posted Version 4.0 at http://www.nwra.com/resumes/andreas/software.php, where it can be freely downloaded. This new version is built around the new air-sea drag relation that Andreas et al. (2012) developed and is tested with ten times as much data as was Version 3.4.

## RELATED PROJECTS

Andreas is in the third year of an ONR project funded by the Marine Meteorology Program: "Predicting the Turbulent Air-Sea Surface Fluxes, Including Spray Effects, from Weak to Strong Winds." In that project, he has been collaborating with Larry Mahrt and Dean Vickers, who is a subcontractor, to develop a bulk flux algorithm from a large air-sea flux dataset that they have assembled as part of the project. A bulk flux algorithm can be used in large-scale models to couple the atmosphere to the sea by providing the flux boundary conditions on the air-sea exchanges of momentum and sensible and latent heat. The turbulent flux data that we have collected under the current project can augment the data already assembled under this Andreas-Mahrt project. Likewise, the spray concentration measurements that we have made under the current project can augment information about the spray generation function that is crucial to the Andreas-Mahrt project.

## REFERENCES

Andreas EL. 2010. Spray-mediated enthalpy flux to the atmosphere and salt flux to the ocean in high winds. *J. Phys. Oceanogr.* **40**: 608–619.

Andreas EL, Persson POG, Hare JE. 2008. A bulk turbulent air-sea flux algorithm for high-wind, spray conditions. *J. Phys. Oceanogr.* **38**: 1581–1596.

Andreas EL, Jones KF, Fairall CW. 2010. Production velocity of sea spray droplets. *J. Geophys. Res.* **115**: C12065, doi:10.1029/2010JC006458.

Andreas EL, Mahrt L, Vickers D. 2012. A new drag relation for aerodynamically rough flow over the ocean. *J. Atmos. Sci.* **69**: 2520–2537.

Fairall CW, Banner ML, Peirson WL, Asher W, Morison RP. 2009. Investigation of the physical scaling of sea spray spume droplet production. *J. Geophys. Res.* **114**, C10001: doi:10.1029/2008JC004918.

Finstad KF, Lozowski EP, Gates EM. 1988. A computational investigation of water droplet trajectories. *J. Atmos. Oceanic Technol.* **5**: 160–170.

Jones KF. 1996. Ice accretion in freezing rain. *CRREL Report 96-2*, Cold Regions Research and Engineering Laboratory, Hanover, New Hampshire, 23 pp.

Jones KF, Andreas EL. 2012. Sea spray concentrations and the icing of fixed offshore structures. *Quart. J. Roy. Meteor. Soc.* **138**: 131–144.

Jones KF, Andreas EL. 2013. Winter measurements of sea spray at Mt. Desert Rock. *Proceedings of the 16$^{th}$ International Workshop on the Atmospheric Icing of Structures*, St. John's Newfoundland, September 2013.

Lawrence MG. 2005. The relationship between relative humidity and the dewpoint temperature in moist air. *Bull. Amer. Meteor. Soc*. **86**: 225–233, doi:10.1175/BAMS-86-2-225.

Lewis ER, Schwartz SE. 2004. *Sea Salt Aerosol Production: Mechanisms, Methods, Measurements, and Models—A Critical Review*. Geophysical Monograph 152, AGU: Washington, DC, 413 pp.

Nauman JW. 1984. Superstructure icing observations on the semisubmersible *Ocean Bounty* in Lower Cook Inlet, Alasks. In *Proceedings of the 2nd International Workshop on Atmospheric Icing*, EFI Technical Report 3439, pp. 71–79, Trondheim, Norway, 19–21 June 1984.

## PUBLICATIONS

Andreas EL, Jordan RE, Mahrt L, Vickers D. 2013. Estimating the Bowen ratio over the open and ice-covered ocean. *Journal of Geophysical Research*, **118**, doi:10.1002/jgrc.20295. [in press, refereed]

Jones KF, Andreas EL. 2012. Sea spray concentrations and the icing of fixed offshore structures. *Quarterly Journal of the Royal Meteorological Society*, **138**, 131–144. [published, refereed]

Jones KF, Andreas EL. 2013. Risk of sea spray icing to offshore structures. *Proceedings of the Twenty-third (2013) International Offshore and Polar Engineering Conference*, Anchorage, Alaska, July 2013,1203-1209. [published]

Jones KF, Andreas EL. 2013. Winter measurements of sea spray at Mt. Desert Rock. *Proceedings of the 16$^{th}$ International Workshop on the Atmospheric Icing of Structures*, St. John's Newfoundland, September 2013 [published]

Yang J, Jones KF, Yu W, Morris R. 2012. Simulation of in-cloud icing events on Mount Washington with the GEM-LAM. *Journal of Geophysical Research–Atmospheres*, **117**, D17204, doi:10.1029/2012JD017520. [published, refereed]

## HONORS/AWARDS/PRIZES

Ed Andreas was just named a Fellow of the American Meteorological Society.